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Frank S. Henyey, P.I.

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North Pacific Acoustic Laboratory (NPAL) is the name for a set of experiments on long-range acoustic propagation through the ocean. For a sound to travel far in the ocean, its frequency must be low; sound at 70HZ was frequently used in NPAL experiments. It is common for the propagation of sound to be described in terms of ray tracing, a theory that assumes the frequency is high. An obvious question is whether NPAL frequencies used in experiments are high enough to allow use of ray tracing. The PI wrote a ray trace program and an internal wave simulation program, more realistic than other programs in existence. The research showed that rays could not be correct for the effects of internal waves, but did not find out in what way they were wrong. This research has been continued on ONR grant N00014-05-1-0282.

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Final Technical Report

# NPAL Modeling—Internal Wave Effects/Theory and Modeling of Internal Wave Effects on Acoustic Propagation

ONR Grant N00014-99-1-0715
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Frank S. Henyey, P. I.

North Pacific Acoustic Laboratory (NPAL) is the name for a set of experiments on long-range acoustic propagation through the ocean. For a sound to travel far in the ocean, its frequency must be low; sound at 70 Hz was frequently used in NPAL experiments. It is common for the propagation of sound to be described in terms of ray tracing, a theory that assumes the frequency is high. An obvious question is whether NPAL frequencies used in experiments are high enough to allow use of ray tracing.

When only the large-scale structure of the ocean is used to describe the variability of the speed of sound, ray tracing does work, and accurate results are obtained. Yet there are features of the received sound that depend on small-scale structures. The small scales are largely due to internal waves. It had been assumed that ray tracing would be accurate with the small scales present. A number of ray trace computer programs were written by others and results had disseminated. At the time this grant began, there were claims that acoustic rays in the ocean exhibited "chaos", as has been established for other physical systems, such as electrons in a plasma apparatus used in controlled fusion energy research. The P.I. doubted the validity of this claim. The chaos model might be correct if the internal wave field repeated every 50 km or so (or possibly some multiple of 50 km). The reason for doubt of the claim is that real internal waves don't have a periodicity.

The P.I. began the research by writing a ray trace program, with care taken to make the results be exceptionally accurate, and an internal wave simulation program that was much more realistic than any other that had been written. The P.I. avoided periodicity at short distances of 50, 100, 150, etc. km, but, rather, the simulated internal waves repeated only after 1000 km. These simulations were run for very many thousands of rays that would have been identical if there were no small-scale structure. The results were that the chaos idea failed, whereas the much older transport ideas qualitatively agreed with the simulations. One important difference is that the chaos ideas predict a bimodal distribution of estimates of the Lyaponov exponent, one component centered on zero value for the non-chaotic rays, and one centered on a positive value for the chaotic rays. The transport ideas, on the other hand, predict a unimodal distribution; all rays are part of the same component. This latter behavior was what the simulations showed, with no possibility of the bimodal structure.

In examining the simulation results in detail, it became clear that the ray model could not be correct. There were inconsistencies with general properties of wave propagation. The

small scale internal waves created very narrow beams that persisted for hundreds of kilometers, while actual beams that small at the experimental frequencies would not persist for even ten kilometers. Moreover, even if the rays were valid, there is no known formula to compute their wave field. Work of Airy, of Chester, Friedman and Ursell, and of Maslov, and of followers of these authors has led to a number of enhanced expressions for the wave field of a set of rays when the frequency is not high enough for the simplest formula, but none of these expressions come even remotely close to what is needed for the configuration of rays that the simulation finds, at the experimental frequencies used.

The research described above showed that rays could not be correct for the effects of internal waves, but did not find out in what way they were wrong. The P.I. teamed up with Mike Wolfson (APL/UW) to compare wave solutions with the ray-tracing approximation. They used a "parabolic" (more correctly, paraxial) equation, for which a numerical solution is practical, which is not true for the more correct Helmholtz equation. Ray tracing is equally easy for both equations. Other than the ray approximations, the calculations were identical. They first looked at the arrival time distribution of a typical "arrival", i. e., the energy associated with a single ray of the large-scale ocean. Then they looked at the distribution in depth of the "deep arrivals," that come below the large-scale rays. In both cases, the rays were spread out in a rather accurate Gaussian distribution, while the wave equation showed a much narrower peak, with a very diffuse distribution surrounding it. This led us to consider a problem that is not practical in real-world experiments, but easy in computer experiments. They launched a single acoustic mode, and then after only 50 km, we decomposed the sound field into normal modes. They found the same behavior as for the long ranges; the ray trace showed a Gaussian distribution, while the wave equation showed most of the energy in the same mode we started with, with a diffuse scattered component. This allowed them to understand how ray tracing failed. They were able to make exactly solvable "toy" models that have the same properties. If one imagines the propagation as consisting of discrete scattering events, the wave's phase shift for an event can be small compared to one radian, or it might be large. If it is large, then ray tracing gives correct results. If, on the other hand, it is small, the unscattered peak occurs, and the remainder of the energy is much more spread out than any rays are.

The results of these studies have been regularly presented at meetings of the NPAL group.

The P.I. also participated in the planning for the Loapex experiment. This experiment was designed to concentrate on propagation issues more than on tomography measurements, and is proving to be valuable in improving our understanding of the propagation. In particular, the East-West orientation of the experiment, and the configuration of the deep receiver array were included for the purposes of understanding the propagation.

This research is being continued by the P.I. on ONR grant N00014-05-1-0282.